Fermi National Accelerator Laboratory

Search for Long-lived Parents of Z^0 Bosons in p̄p Collisions at $\sqrt{s} = 1.8$ TeV

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Search for Long-Lived Parents of Z^0 Bosons in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We search for new long-lived particles which decay to Z^0 bosons by looking for $Z^0 \to e^+ e^-$ decays with displaced vertices. We find no evidence for parent particles of the Z^0 with long lifetimes in 90 pb^{-1} of data from the CDF experiment at Fermilab. We set a cross section limit as a function

of the lifetime of the parent particle for both a generic Z^0 parent and a fourth-generation, charge $-\frac{1}{3}$ quark that decays into $Z^0 b$.

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In the standard model, there are no particles with mass above 20 GeV and lifetime greater than 10^{-20} seconds. In particular, there are no metastable particles that decay into a Z^0 boson. In $p\bar{p}$ collisions, the Z^0 can be produced either in the primary interaction through quark-antiquark annihilation or possibly from a neutral-current decay of the short-lived top quark ($t \rightarrow Z^0 c$). By searching for $Z^0 \rightarrow e^+ e^-$ with the $e^+ e^-$ vertex displaced from the $p\bar{p}$ interaction point, we are sensitive to non-standard-model sources of the Z^0.

There are a number of extensions to the standard model that can accommodate a long-lived parent to a Z^0. One class of models contains a fourth-generation, charge $-\frac{1}{3}$ b' quark. A b' with mass less than $m_Z/2$ has been ruled out by experiments at the LEP electron-positron collider [1]. A recent analysis by the DØ collaboration has excluded the existence of a b' with mass $m_Z/2 < m_{b'} < m_Z + m_b$ which decays via the flavor changing neutral current, $b' \rightarrow b + \gamma$ [2]. A more massive b' could decay into a Z^0 and a bottom quark ($b' \rightarrow b + Z^0$) through a loop induced flavor-changing neutral current [3]. This is expected to be a dominant decay mode for $m_Z + m_b < m_{b'} < m_t, m_{t'}$, where $m_{t'}$ is the mass of the t' quark (the partner of the b'). This decay may have a small partial width due to the neutral current decay and the fourth-generation quark mixing angles [4]. The competing charged current decay mode, $b' \rightarrow W^- c$, could also have a very small partial width since it depends on the mixing of quarks separated by two generations. This analysis searches for a long-lived b' in the mass region above the Z^0 through the decay chain $b' \rightarrow Z^0 b$ where $Z^0 \rightarrow e^+ e^-$.

Some models of supersymmetry also allow for long-lived particles which decay to Z^0. For example, a low-energy symmetry-breaking model [5] in which the gravitino is the lightest stable particle allows for a long-lived parent of the Z^0. This model predicts that the lightest neutralino, which could decay into a Z^0 and a gravitino, $\tilde{N}_1^0 \rightarrow Z^0 + \tilde{G}$, may have a long lifetime because of the small coupling constant to the gravitino.

The data used in this analysis were collected with the Collider Detector at Fermilab (CDF) during the 1993-95 Tevatron run, and correspond to an integrated luminosity of 90 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The CDF detector is described in detail elsewhere [6]. We describe here only the detector components most relevant to this analysis. The central tracking chamber (CTC), which is immersed in a 1.4 T solenoidal magnetic field, measures the momenta and trajectories of charged particles in the region $|\eta| < 1.1$ [7]. The four-layer silicon vertex detector

(SVX) [8], located just outside the beam pipe, provides precise tracking in the plane transverse to the beam direction, giving a track impact parameter relative to the beam line with a resolution of $(13 + 40/P_T)$ μm, where P_T is the transverse momentum of the track in GeV/c. The transverse profile of the Tevatron beam is circular with an rms width of ~ 35 μm. Electromagnetic and hadronic calorimeters surround the solenoid. This analysis uses the central detector region ($|\eta| < 1$), where there is full tracking efficiency.

To find a long-lived parent of the Z^0, we search for events containing an electron-positron pair with a mass consistent with a Z^0 and a vertex displaced from the $p\bar{p}$ interaction point. We begin with a sample of electron-positron pairs, each lepton having $|\eta| < 1$ and $E_T > 20$ GeV [9]. The electron and positron are each required to be isolated, having a total calorimeter E_T in an $\eta - \phi$ cone of radius 0.4 around the lepton of no more than 1.15 times the lepton E_T. We also require that the electron-positron invariant mass be in the range $76.2 < M_{ee} < 106.2$ GeV/c^2 as calculated from the calorimeter energies and the track directions. Because precision tracking measurements are critical to the determination of the lifetime of the parent particle, track quality cuts are applied which have been optimized using a high-statistics sample of $J/\psi \rightarrow \mu^+\mu^-$ events. These include minimum numbers of hits in the SVX and CTC as well as a maximum χ^2 for the track fit. The electron and positron tracks are fit to a common vertex, and a good vertex fit is required. Events are removed if the track pair is within 0.02 radians of being back-to-back ($\Delta\phi$ cut), since nearly collinear tracks have a large uncertainty in the vertex position. The invariant mass spectrum of the 703 events that pass all cuts is shown in Figure 1.

To search for long-lived Z^0 parents, we measure L_{xy}, the distance in the transverse $(r - \phi)$ plane between the $p\bar{p}$ interaction point and the e^+e^- vertex. For a long-lived parent, $L_{xy} = \gamma\beta_{xy}ct$, where t is the proper decay time and β_{xy} is the transverse component of the parent's velocity divided by c. L_{xy} is a signed quantity, the sign being that of the dot product between two vectors in the transverse plane: the net P_T of the e^+e^- pair and the vector pointing from the $p\bar{p}$ interaction point to the e^+e^- vertex. L_{xy} significantly less than zero is generally due to tracking mismeasurement. For standard model direct Z^0 production ($q\bar{q} \rightarrow Z^0 \rightarrow e^+e^-$), we expect $L_{xy} \approx 0$, since the Z^0 lifetime is negligible. L_{xy} significantly greater than zero suggests that either the Z^0 is a decay product of a long-lived parent particle or there is tracking mismeasurement.

The L_{xy} distribution is shown in Figure 2 after all of the cuts have been applied. The observed distribution is in good agreement with the expected L_{xy} distribution for prompt Z^0s, obtained from the L_{xy} uncertainty measured in each event from propagation of tracking errors. Events with large $|L_{xy}|$ that are due to mismeasurement should be

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symmetric around zero. The number of events with L_{xy} significantly less than zero is thus an effective measure of this background. To search for long-lived sources, we have examined the events with $|L_{xy}| > 0.1$ cm, the point beyond which less than one event is expected from prompt Z^0s based on the L_{xy} uncertainty distribution. We observe 1 event with $L_{xy} > 0.1$ cm and 3 events with $L_{xy} < -0.1$ cm. Thus, there is no evidence for a long-lived parent of a Z^0. We proceed to set limits based on this observation.

The production cross section times branching ratio [10] for long-lived parent particle(s) decaying to a Z^0 and passing our data selection criteria is calculated by normalizing to the observed prompt Z^0 boson signal. It can be written as

$$\sigma \cdot Br \cdot A_X = \frac{n_X \cdot A_Z \cdot \sigma_Z \cdot Br(Z^0 \to e^+ e^-)}{n_Z \cdot F_{DY} \cdot \epsilon_{\Delta\phi} \cdot \epsilon_{\chi^2} \cdot \epsilon_{L_{xy}}}$$

where A_X is the acceptance for finding both the electron and the positron in the geometry of the detector, n_X is the number of events seen with a significant decay length (> 0.1 cm), $A_Z = 22 \pm 1\%$ is the probability that the e^- and e^+ from a directly produced Z^0 are in the central part of the detector, $\epsilon_{\Delta\phi}$ is the efficiency of the opening angle cut ($87 \pm 1\%$ in the direct Z^0 sample), $\epsilon_{\chi^2} = 94 \pm 1\%$ is the efficiency of the χ^2 cut, $\epsilon_{L_{xy}}$ is a correction factor for the number of events seen in the L_{xy} window (0.1 cm$< L_{xy} < 1.5$ cm), and $F_{DY} = 0.96 \pm 0.01$ is a factor to correct for Drell-Yan contamination in the prompt Z^0 sample. We normalize to the measured Z^0 cross section by using $\sigma_Z \cdot Br(Z^0 \to e^+ e^-) = 231 \pm 12$ pb [11] and $n_Z = 859$, the number of Z^0 events left after the electron pair and tracking cuts. For a fixed $\lambda_{xy} \equiv \gamma\beta_{xy}c\tau$, where τ is the lifetime of the parent particle, the efficiency in the L_{xy} window is $\epsilon_{L_{xy}} = e^{\frac{-0.1 \text{ cm}}{\lambda_{xy}}} - e^{\frac{-1.5 \text{ cm}}{\lambda_{xy}}}$.

For the 95% confidence level upper limit on the cross section, we make the conservative assumption that there is no background and thus do not perform a background subtraction. We also conservatively use the opening-angle cut efficiency measured in the direct Z^0 sample. Z^0 bosons from heavy particle decay would generally be boosted in the transverse direction, thus increasing the cut efficiency. We use a Poisson distribution based on the one observed event smeared by the gaussian systematic uncertainties in the acceptance and efficiencies. We find the 95% confidence level cross section limit to be

$$\sigma \cdot Br \cdot A_X \leq \frac{0.36}{\left(e^{\frac{-0.1 \text{ cm}}{\lambda_{xy}}} - e^{\frac{-1.5 \text{ cm}}{\lambda_{xy}}}\right)} \text{ pb}$$

The cross section limit as a function of λ_{xy} is shown in Figure 3.

A cross section limit can also be determined for b' pair production. The b' quark should have the same production cross section as a function of mass as the top quark because both are pair-produced via the strong interaction. We would also expect to find several quark jets in the event if a b' pair were produced, for example $q\bar{q} \to b'\bar{b}' \to bZ^0\bar{b}Z^0 \to be^+e^-\bar{b}q\bar{q}$. We have thus required that there be 2 or more jets with $|\eta| < 2$ and $E_T > 10$ GeV. The L_{xy} distribution for the 27 events surviving the jet cut is shown in the inset in Figure 2. The value of L_{xy} above which we expect less than 1 event is now 0.01 cm. We find one such event in our data sample.

The cross section limit for b' pair production is given by

$$\sigma_{b'\bar{b}'} \cdot Br(b'\bar{b}' \to Z^0 + X \to e^+e^- + X) =$$

$$\frac{n_{b'} \cdot A_Z \cdot \sigma_Z \cdot Br(Z^0 \to e^+e^-)}{n_Z \cdot F_{DY} \cdot A_{b'} \cdot \epsilon_{jet} \cdot \epsilon_{\Delta\phi} \cdot \epsilon_{\chi^2} \cdot \epsilon_{L_{xy}} \cdot F_I}$$

where $n_{b'}$ is the number of events seen with $L_{xy} > 0.01$ cm. If b' always decays into $Z^0 b$, the probability that at least one Z^0 decays into e^+e^- is 0.0662. The quantities $\epsilon_{\Delta\phi}$ (the efficiency of the opening angle criterion), ϵ_{jet} (the efficiency of the jet requirement), and $A_{b'}$ (the probability of observing an electron and a positron in the detector fiducial volume) all depend on the mass of the b'. We use the Herwig Monte Carlo to estimate these quantities as a function of the b' mass [12]. We use $\gamma\beta_{xy}$ distributions for the b' from the Monte Carlo to estimate $\epsilon_{L_{xy}}$. This efficiency depends on the mass of the b' and the lifetime, which is a function of the fourth-generation mixing angles between the quarks. For a particular lifetime, we find $\epsilon_{L_{xy}}$ by calculating $e^{\frac{-0.01\ \text{cm}}{\lambda_{xy}}} - e^{\frac{-1.5\ \text{cm}}{\lambda_{xy}}}$ for each event and averaging the entire Monte Carlo sample. We also include in the calculation of the b' cross section a factor $F_I = 0.92 \pm 0.05$ that corrects for the reduced electron isolation efficiency due to the expected jets in a b' event. The excluded lifetimes for a b' of mass 110 GeV/c^2 are shown in the inset in Figure 3. The excluded region of the b' mass versus lifetime plane is shown in Figure 4 using the theoretical cross sections in [13] and the assumption that $Br(b' \to Z^0 + b) = 100\%$.

In conclusion, we find no evidence for new particles with a long lifetime decaying to Z^0 bosons. We set 95% confidence-level cross section upper limits on new particle production as a function of λ_{xy}. A range in mass and lifetime for a fourth generation b' quark decaying to $Z^0 b$ has been excluded.

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[4] A search for a short-lived b' quark by looking at Z^0 plus three or more jets, one of which is identified as a b quark, is in progress within CDF.

[5] S. Ambrosanio *et al.*, *Phys. Rev. D* **54**, 5395 (1996).

[6] F. Abe *et al.*, *Nucl. Inst. Meth. A* **271**, 387 (1988).

[7] The coordinate system at CDF has been defined so the z-axis is the proton beam direction, θ is the angle from the positive z-axis, ϕ is the azimuthal angle, and r is the distance from the z-axis. Pseudorapidity is defined by $\eta \equiv -\ln\tan\frac{\theta}{2}$. Transverse momentum is defined by $P_T \equiv P\sin\theta$, and transverse energy deposited in the calorimeters is $E_T \equiv E\sin\theta$.

[8] P. Azzi *et al.*, *Nucl. Inst. Meth. A* **360**, 137 (1995).

[9] The electron selection criteria are described in F. Abe *et al.*, *Phys. Rev. D***52**, 2624 (1995). For this analysis, both leptons are required to have Had/EM < 0.125. At least one must have track $P_T > 13$ GeV, $L_{\mathrm{shr}} < 0.2$, $|\delta z| < 5$ cm, $|\delta x| < 3$ cm, and $\chi^2_{\mathrm{strip}} < 10$.

[10] $\sigma\cdot Br$ varies for the particular decay process. For single particle production, $\sigma\cdot Br = \sigma_X\cdot Br(X \rightarrow Z^0 + Anything)\cdot Br(Z^0 \rightarrow e^+e^-)$. For pair production, the branching ratio will depend on the probability of producing at least one Z^0 that decays to e^+e^-.

[11] F. Abe *et al.*, *Phys. Rev. Lett.* **76**, 3070 (1996).

[12] G. Marchesini *et al.*, *Comput. Phys. Commun.* **67**, 465 (1992).

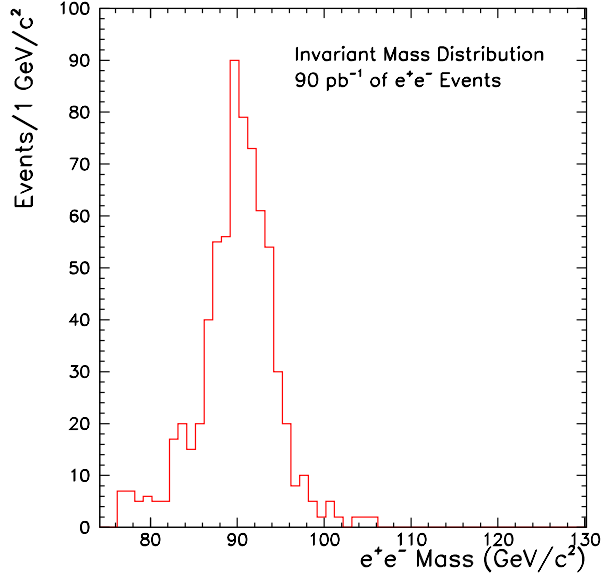[13] E. Laenen *et al.*, *Phys. Lett. B* **321**, 254 (1994).

FIG. 1. The e^+e^- invariant mass distribution after applying all cuts.
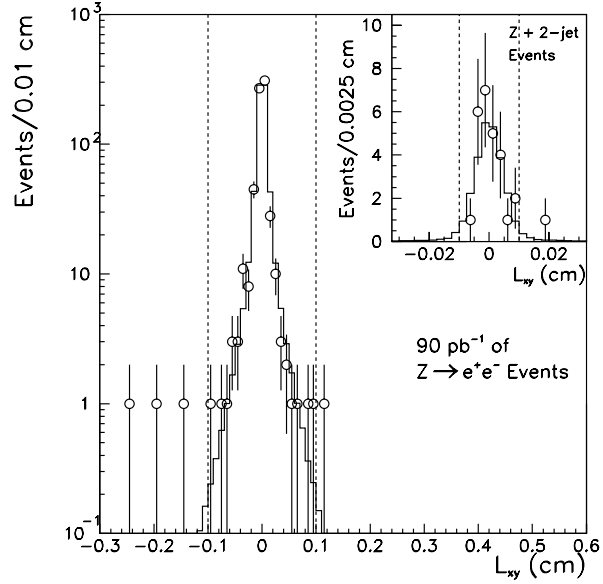

FIG. 2. The L_{xy} distribution of the Z^0s after applying all cuts. The data are represented by the circles. The histogram is the expected L_{xy} distribution for prompt Z^0s based on the measured L_{xy} uncertainty in the event sample. The inset shows the distribution after the 2 jet requirement is applied. The vertical dashed lines separate the prompt and non-prompt regions.
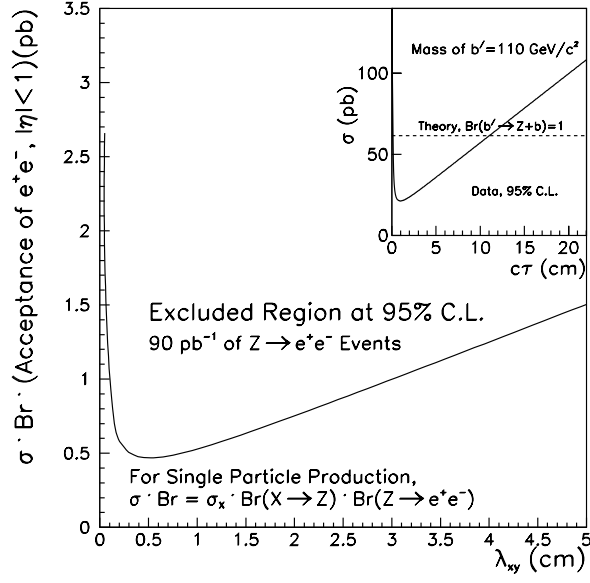
FIG. 3. The 95% confidence level upper cross section limit for $\sigma \cdot Br$ times the acceptance for an electron-positron pair to be within the detector as a function of fixed λ_{xy}. Cross sections above the curve have been excluded at the 95% confidence level. The inset shows the exclusion curve and the theoretical prediction for a b' quark of mass 110 GeV/c^2 as a function of its lifetime, assuming 100% decay into $Z^0 b$.
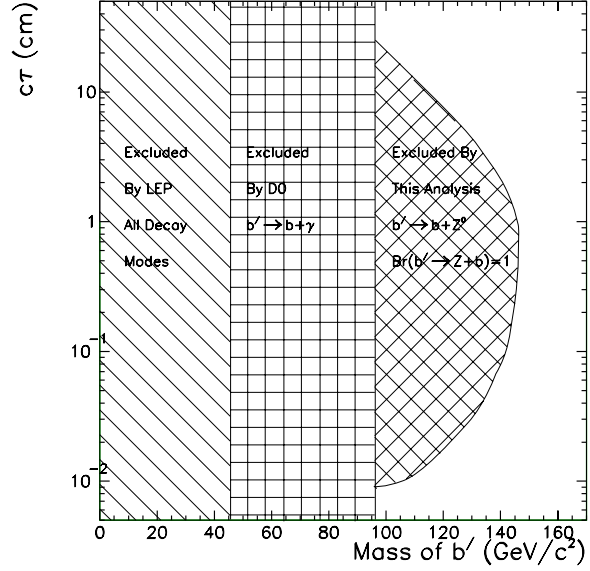

FIG. 4. The hatched areas in this plot represent the 95% confidence-level regions of b' mass and lifetime that have been excluded. For $c\tau = 1$ cm, we have excluded up to a mass of 148 GeV/c^2.

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